The First Direct Spectroscopic Detection of a White Dwarf Primary in an AM CVn System

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ABSTRACT

We report the results of a synthetic spectral analysis of Hubble STIS spectra of the AM CVn-type cataclysmic variable CP Eri obtained when the system was in quiescence. The FUV spectrum is best fitted by a helium-dominated, hybrid composition (DBAZ) white dwarf with $T_{eff} \sim 17,000K \pm 1000$K, log g$\sim$ 8, He abundance $\sim$ 1000$\times$ solar, H abundance $\sim$ 0.1$\times$ solar, metallicity Z $\sim$ 0.05$\times$ solar, $V \sin i \sim$ 400 km/s$\pm$100 km/s. This is the first directly detected primary white dwarf in any AM CVn and the surface abundance and rotation rate for the white dwarf primary are the first to be reported for AM CVn systems. The model-predicted distance is $\sim$ 1000 pc. The spectral fits using pure He photospheres or He-rich accretion disks were significantly less successful. Based upon the analysis of our FUV spectra, CP Eri appears to contain a hybrid composition DBAZ white dwarf with a metallicity which sets it apart from the other two AM Cvn stars which have been observed in quiescence and are metal-poor. The implications of this analysis for evolutionary channels leading to AM CVn systems are discussed.

Key Words: Stars: AM CVn systems, white dwarfs, accretion

1. Introduction

The AM CVn objects, like the essentially pure helium DB white dwarfs, are very H-poor and appear to be dominated by nearly pure helium accretion disks in the optical during outburst and (for those which have low states), in quiescence. In their bright states they are spectroscopically similar to the spectra of AM CVn in its continual bright state in which the absorption lines of an optically thick helium disk and wind dominate their optical and FUV spectra (e.g., Groot et al. 2001 and references therein).

AM CVn objects are widely regarded as interacting binary white dwarfs in which the less massive degenerate companion (with $M_{wd} < 0.1 M_{\odot}$) fills its Roche lobe and transfers He-rich gas through an accretion disk to the more massive companion white dwarf primary. The basic model was first proposed by Paczynski (1967), Faulkner, Flannery and Warner (1972) with their binary nature first confirmed by Nather, Robinson and Stover (1981). The properties of these systems are comprehensively reviewed by Warner (1995).

In addition to the interest in the evolutionary history which leads to their nearly pure helium composition and the accretion physics and physical conditions which prevail during helium accretion, these objects may contribute up to 25% of the Type Ia supernova production rate (Nelemans et al. 2001) although recent work suggests it is less than 1% (Solheim & Yungelson, 2005)

The best distance estimates for AM CVns are based on the Hubble distances given by P.Groot (Nijmegen workshop on AM CVn stars, July 2005). For the two systems, CR Boo and V803 Cen, most similar to CP Eri, i.e. having outburst/quiescence states and similar orbital periods, $M_v = 6.5$ for CR Boo and 5.4 for V803 Cen (for their high states). If we assume for CP Eri an average $M_v = 6 \pm 0.5$ for the high state, we get a distance $1.2^{+0.8}_{-0.4}$ kpc.

The systems CR Boo, CP Eri, V803 Cen, 2QZJ142701.6-012310, KL Dra, and SN2003aw are the only systems of the roughly dozen known AM CVn objects to have both high states and low states in analogy with their H-rich dwarf novae and nova-like counterparts. CP Eri, the topic of this Letter, has an orbital period of 28.73 minutes, an optical brightness range of 16.5 in outburst and 19.7 in quiescence with broad shallow optical He I absorption in outburst and, in quiescence, double-peaked He I and He II emission as well as Si II emission in the optical (Abbott et al. 1992). Abbott et al. (1992) did not detect H in either high or low state optical spectra.

A difficult obstacle to gaining information on the underlying stars has been that the

quiescent spectra are rare and of poor signal-to-noise due to the objects' faintness both in the optical and the far UV. In this Letter, we report the analysis of the first FUV spectrum of a quiescent AM CVn that displays substantial continuum flux. All other AM CVn systems that display substantial continuum flux are in outburst like AM CVn itself.

2. Hubble STIS Observation

We obtained two HST STIS spectra of CP Eri on 11 September, 2000 with the STIS FUV/MAMA configuration and the G140L grating through the 52×0.2 aperture with exposure times of 1919 s and 2580 s for spectra O5B606010 and O5B606020 respectively. The STIS CCD acquisition image obtained immediately before the G140L spectrum was used to measure the optical brightness of CP Eri during the HST observations. The image was obtained with the F28×50LP filter, which has a pivot wavelength at 7229 Å, and a band width of 5400–10 000 Å, roughly comparing to an R-band filter (see Araujo-Betancor et al. 2005 for details of the procedure).

Unlike the optical spectrum of CP Eri seen in quiescence, the FUV spectrum contains many observed absorption features including a strong feature at Lyman Alpha, strong C III (1175), C II (1335), Si II (1260, 1265), C I (1270), OI + Si III (1300), C II (1335), C I (1356, 1490, 1657), Si II (1526, 1533) and moderately strong emission features at Si IV (1393, 1400), possible N V (1238, 1242) emission, and possible He II (1640) emission.

3. Synthetic Spectral Fitting with Helium Disks and Photospheres

The grid of helium accretion disk models described by Nasser et al. (2001) were compared with the HST STIS spectrum of CP Eri over the effective wavelength range of the STIS spectrum, 1150Å– 1716Å. The helium accretion disks are steady state NLTE

models which are more appropriate for the high state of AM CVn systems. However, as a first approximation to the accretion disk during a low state, we applied the optically thick models to CP Eri's spectrum.

The composition and designation of the disk models (see Table 1 below) is as follows. The disk models labeled cperim4i* have He/H =1000, Z = 0.001 solar, and an outer radius (of the outermost annulus) of 15 white dwarf radii. The "i" is the inclination angle in degrees. The disk model cperim9i45 has He/H = 105, CNO abundances = 3, 900, 1.5× solar respectively, and outermost disk radius = 15 WD radii. The disk model cperim10i* has He/H = 105, metallicity Z = solar and outer disk radius r_{max} = 8 WD radii. Curiously, the disk fits are improved considerably below 1350AA if Fe is overabundant because of the large number of low exitation Fe lines whose collective absorption eats away at the continuum and broaden line profiles. This is especially noticeable at 1260AA. On the hand, when the same disk models are applied to AM CVn itself, the elevation of Fe does not result in a better fit. It is possible, this difference between CP Eri and AM Cvn may point to different progenitor evolution.

In preparation for the model fitting, emission lines in the data were masked out. We used a χ^2 minimization fitting routine wddiskfit which yields the χ^2 value, scale factor and the distance computed from the scale factor. We have tabulated the results in Table 1 where the first column lists the model designation (see above), second column the χ^2 value third column the scale factor, the last column the distance in kiloparsecs. To obtain the distances from the model normalization for each fit, we scaled down by a factor corresponding to the magnitude difference between the high state (16.5) and the low state (19.7). This corresponds to a factor of 0.0524 or a distance ratio 0.229. This yields distances of 1.34, 1.04, 1.21, 1.27, 1.15 kpc, which are all quite reasonable. The best-fitting accretion disk model is cperi4i45, which has He/H = 1000, Z=0.001(including Fe), a disk inclination angle

of 45 degrees and a $\chi^2 = 2.4162$. The "best-fit" helium accretion disk fit is displayed in figure 1.

We also explored the possibility that the STIS spectrum of CP Eri in its low brightness state, like the FUV spectra of the shortest period dwarf novae, is produced by a white dwarf with essentially no contribution from an accretion disk. Therefore, we constructed an initial grid of helium-rich photospheres with He/H = 10^{-5}, He = 1000, and Z = 10^{-4}. The grid covers the following parameter ranges: temperatures of 15,000K - 30,000K in steps of 3000K, surface gravities log g = 7.5, 8.0, 8.5 and rotational velocities $V \sin i = 200$, 400 and 600 km/s. The best-fitting helium-rich photosphere model has $T_{eff} = 15,000$K and log g = 8.0. The rotational velocity is meaningless since the low metallicity model had no strong metal absorption lines to match with the STIS spectrum. This model yielded a $\chi^2 = 2.5702$, a scale factor = 3.29×10^{-4} and a distance of 804 pc for a white dwarf radius $R_{wd}/R_{\odot} = 1.46 \times 10^{-2}$. The best-fitting He photosphere (no H) is displayed in figure 2. However, this model does not fit the absorption lines well.

The rather deep absorption line near 1216Å could not be due to He II at the T_{eff} of the white dwarf indicated by the continuum and by low ionization metal line profile fits. Hence, unless the absorption has a hydrogen interstellar origin, which is unlikely given its breadth, there is a possibility it is photospheric H I Lymanα. Therefore, we explored hybrid composition "DBA" atmospheres in which the dominant element is helium with hydrogen being far less abundant. Assuming that the profile is entirely H I, we kept the gravity fixed at log g = 8 and experimented with various He/H ratios from 102 to 105, metal abundances $Z = 0.5, 0.1, 0.05, 0.005$, $T_{eff} = 14,000, 15,000..., 20,000$K. We found that the optimal He/H ratio needed to replicate the profile is He = 1000, H = 0.1 or He/H = 10000. This ratio is smaller than the stringent He/H ratio characterizing the DB white dwarfs where He/H > 105 in order for Balmer lines not to be detected in their optical spectra (which they

are not). The best-fitting hybrid composition "DBA" model had the following parameters: $\chi^2 = 1.45$, scale Factor S $= 2.224 \times 10^{-4}$, Log g = 8 (fixed), $T_{eff} = 17,000$K, $V \sin i = 400$ km/s, He = 10^3, H = 0.1 and Z = 0.05 and a model-predicted distance of 978 pc. This best-fit model, compared with the STIS data, is shown in figure 3. The hybrid atmosphere fit (H + He) provides a reasonably good fit to both the continuum and the absorption line profiles. The Lymanα absorption profile, assuming no part of it is interstellar, is fit very well with the chosen mix of H and He. However, at the metal abundance of 0.005 solar, while the Si II features at 1260, 1265 are quite well-fit along with C II (1335) and Si II (1526, 1533), the C III (1175), S III + OI (1300) and C I (1356, 1657) absorption features are not well-fit by the model with the synthetic profiles, being considerably weaker than the observed ones. Still, we are encouraged that at least for the Lymanα profile, and the lower ionization lines of C and Si, the fit appears to be somewhat consistent. This model, compared with the best-fit disk model, has a lower χ^2, and fits the metal lines and the Lyman alpha region successfully whereas the best-fit disk model fails to do this.

An additional test of the consistency of our DBAZ composition WD fit is offered by the constraint that the magnitude corresponding to the optical or IR flux of the model is not brighter than the corresponding observed magnitude of CP Eri in the same wavelength range, since it is expected that other sources of systemic light (e.g. a hot spot, accretion disk, secondary) are contributing to the system brightness as well. The STIS F28x50LP magnitude at the time of the HST observation was 19.9. Our best-fit white dwarf model folded with the acquisition filter transmission predicts a magnitude of 20.8, fainter than the observed value.

4. Discussion and Conclusions

Our analysis suggests that CP Eri may not be a typical AM CVn system in that we find a significant abundance of H and a higher metallicity compared with other AM CVn systems such as the well-studied object, GP Com which is metal poor, has shown little evidence of any H and is always seen in a low state. It is obviously important to explore whether the abundance of H from our UV analysis would lead to detected H features in the optical spectrum. While a re-examination of the optical quiescent spectrum of Groot et al. (2001), suggests a possible hint of very weak H I emission features in the optical low state spectrum (see figure 1 in Groot et al. 2001), much higher signal to noise optical spectra are clearly needed. In any case, the metallicity we derive is consistent with the Groot et al. conclusion that CP Eri has higher metallicity than GP Com and CE315, implying that it is not a population II object.

Is it reasonable for the white dwarf in an AM CVn star like CP Eri to be accreting both He and H? If so, what are the implications for the ancestry of CP Eri and other AM CVn objects? There are currently three formation channels favored for AM CVn stars: (1) the double degenerate scenario (Tutukov and Yungelson 1979); (2) semi-degenerate helium star scenario (Iben and Tutukov 1991); and (3) subset of H-rich CVs with evolved secondaries (Podsiadlowski et al.2003). In the latter scenario, a normal H-rich star of mass $\sim 1M_{\odot}$ fills its Roche lobe near the end of, or just after, core Hydrogen burning while the initially non-degenerate and H-rich companion becomes increasingly helium-rich and degenerate during its evolution. In their early evolution, these systems would appear as "normal" H-rich CVs with evolved secondaries. A number of theoretical investigations of all three formation channels have been carried out with stellar evolution codes and binary population synthesis simulations (e.g. Nelemans, G., Portegies, Zwart, S.F., Verbunt, F., & Yungelson, L.R.2001; Podsiadlowski, Han, and Rappaport, S. 2003). Binary stellar

evolution model sequences using a Henyey-type code and including angular momentum losses due to magnetic braking and gravitational wave emission are available for different evolutionary phases of the evolved donor at the onset of mass transfer (Podsiadlowski et al. 2003). Only two of their four evolutionary sequences reach orbital period minima shorter than 55 minutes (75 minutes is the P_{orb} minimum for an H-rich CV). The two sequences correspond to donors with H-exhausted cores of 0.037 and 0.063 $M_{\odot}$ which both transform themselves into nearly pure He degenerates but with a few per cent traces of H remaining. Both of these sequences pass through the range of AM CVn periods twice, once with the period decreasing toward the minimum, once after the period minimum.

Which case might be applicable to CP Eri? Since the degenerate donors in systems before the period minimum have larger amounts of H left in their envelopes, it seems more likely this case would better apply to CP Eri. For its observed P_{orb} (28.73 minutes), the binary population synthesis calculations of Podsiadlowski et al.(2003) yield predicted values of secondary mass $M_2 = 0.100\ M_{\odot}{}^{+0.003}_{-0.021}$, mass transfer rate $\dot{M}= 10^{-9.4}\ M_{\odot}/yr$ and surface hydrogen abundance on the secondary, X = 0.22 for CP Eri if its P_{orb} is decreasing (i.e., it is evolving before the period minimum). If however, CP Eri is evolving after the period minimum (i.e., P_{orb} is increasing), then the simulations predict $M_2 = 0.040\ M_{\odot}{}^{+0.005}_{-0.004}$, $\dot{M}= 10^{-9.8} M_{\odot}/yr$, and $X = 0.03\ M_{\odot}{}^{+0.01}_{-0.03}$.

Since CP Eri's accretor is the only white dwarf in an AM CVn so far with a directly determined photospheric H abundance, we are unable to draw any comparisons with other AM CVn cases. Therefore, analyses of other exposed white dwarfs in these objects are clearly needed.

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Table 1. Helium Accretion Disk Model Fits

Model	χ^2	Scale Factor	Distance(kpc)
cperim4i30	3.15	2.91×10^{-04}	1.34
cperim4i45	2.42	4.82×10^{-04}	1.04
cperim9i45	3.12	3.56×10^{-04}	1.21
cperim10i30	4.52	3.26×10^{-04}	1.27
cperim10i45	4.54	3.99×10^{-04}	1.15

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Warner, B. 1995, in "Cataclysmic Variables" (Cambridge: Cambridge University Press)**CORRECT REF?**

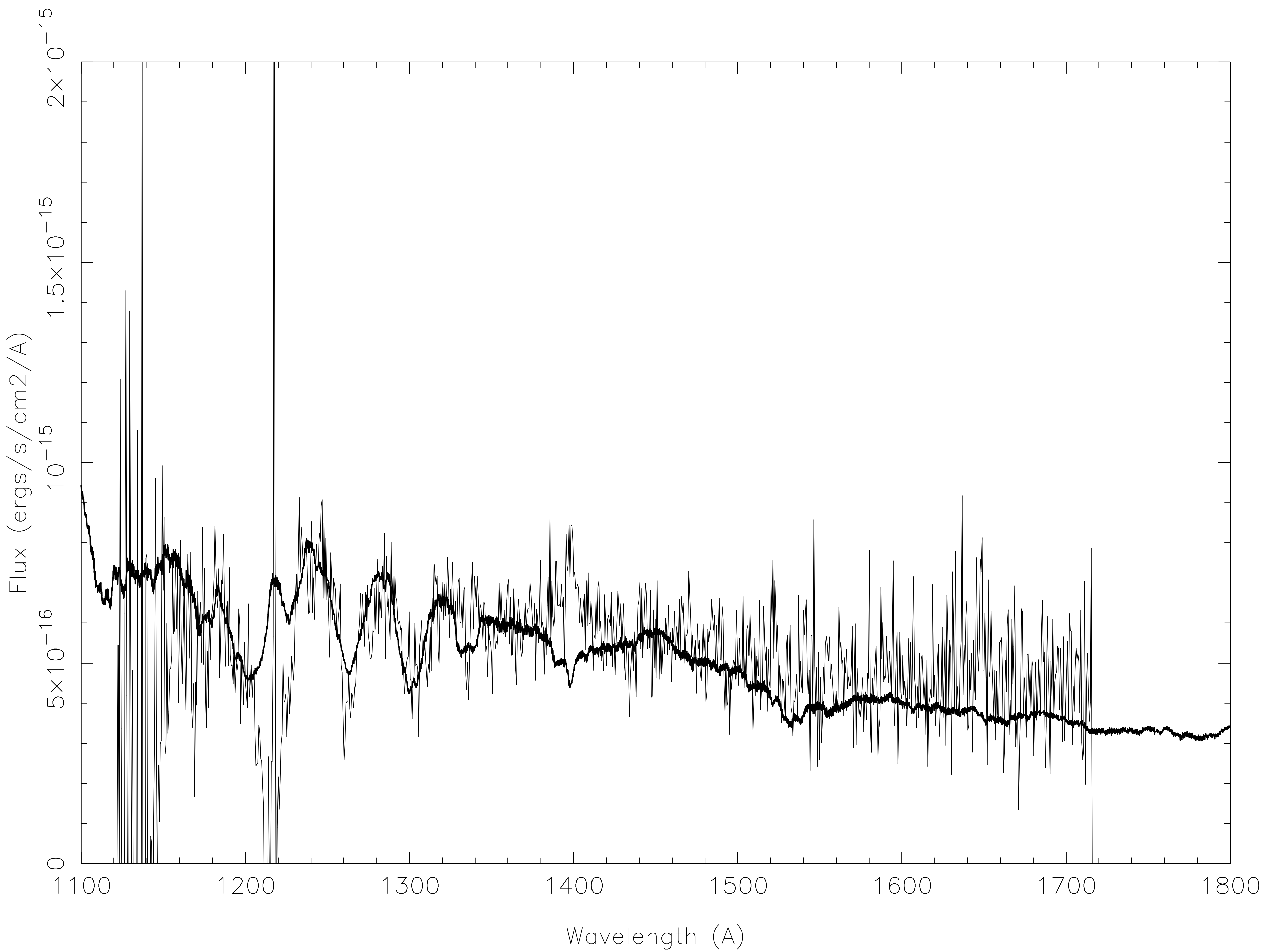
Figure Captions

This manuscript was prepared with the AAS LaTeX macros v5.2.

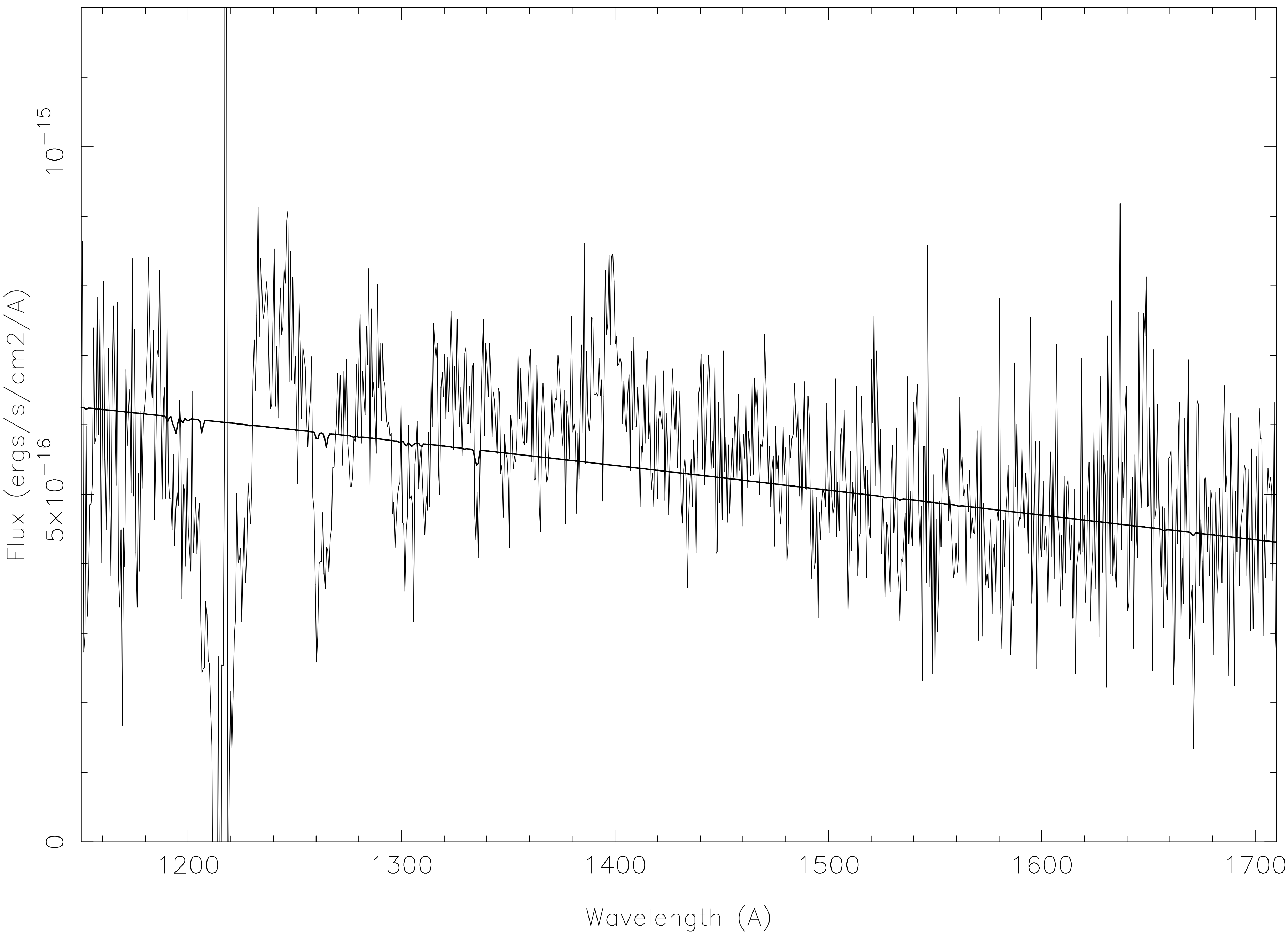
Fig. 1 - The flux distribution, flux versus wavelength, for the best-fitting helium accretion disk model with Z = x.x, and inclination i = 45 degrees compared with the HST STIS spectrum of CP Eri.

Fig. 2 - The flux distribution, flux versus wavelength, for the best-fitting pure helium photosphere model with log g = 8, $T_{eff} = 15,000$K, Z = 0.05, and $V \sin i = 200$ km/s, compared with the HST STIS spectrum of CP Eri.

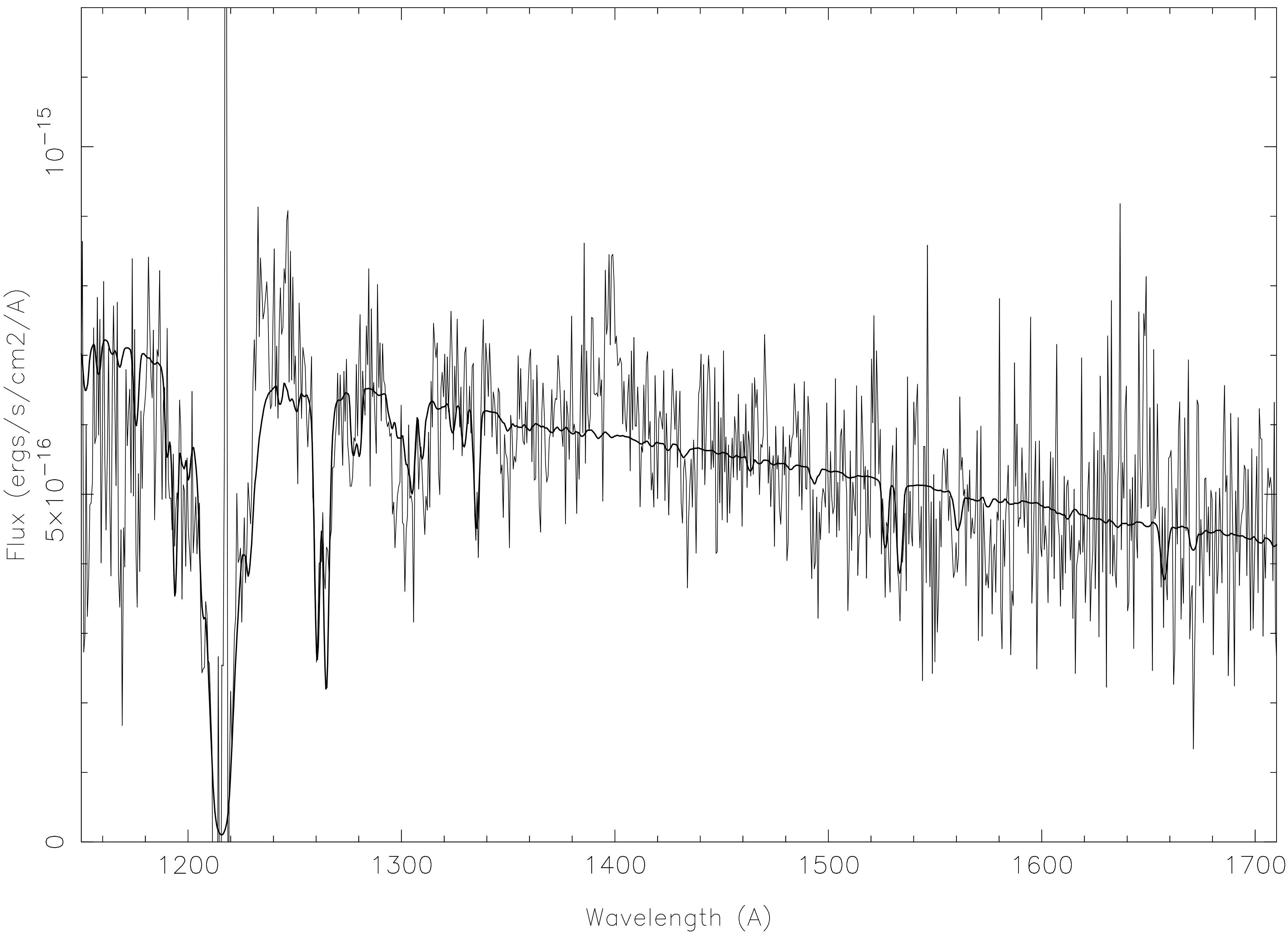
Fig. 3 - The flux distribution, flux versus wavelength, for the best-fitting hybrid composition,"DBAZ", photosphere model with log g = 8, $T_{eff} = 17,000$K, He = 1000, H = 0.1, Z = 0.05, and $V \sin i = 400$ km/s, compared with the HST STIS spectrum of CP Eri.



Flux (ergs/s/cm2/A)
2×10^{-15}
1.5×10^{-15}
10^{-15}
5×10^{-16}
0
1100
1200
1300
1400
1500
1600
1700
1800
Wavelength (A)



Flux (ergs/s/cm2/A)
10⁻¹⁵
5×10⁻¹⁶
0
1200
1300
1400
1500
1600
1700
Wavelength (A)



Flux (ergs/s/cm2/A)
0
5×10^{-16}
10^{-15}
1200
1300
1400
1500
1600
1700
Wavelength (A)